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# Performance Improvement of the Radial Distribution System by using Switched Capacitor Banks

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***Abstract*— Distribution system is the major link which provides supply to the consumers from the high voltage transmission system. The load on the distribution system is not constant and it changes with respect to time throughout the working period. The voltage drop and power losses occur in the distribution system mainly depends on the nature of the load which is applied on the system. The voltage drop and power losses frequently occurs mainly on those systems which are supplying load to the industrial areas, this is mainly because of the existence of more reactive power. To overcome these problems shunt compensation is employed to reduce or suppress those effects to an extent. The main aim of this paper is to determine the specific value of the shunt capacitance required to achieve the permissible voltage tolerance limits and maximum percentage of power loss reduction in a sample two feeder radial distribution system.**

***Index Terms*— Distribution system; Voltage drop; Power loss reduction; Voltage tolerance limits; Shunt compensation.**

## I. INTRODUCTION

The distribution system supplies electric power to end users by means of medium voltage or low voltage distribution systems. The losses which occur at the distribution level contribute a major portion of power system losses. Performance improvement of the distribution system leads to improve the efficiency of power system. Most of the distribution systems are designed in radial manner because it is simple and economical than the other two alternative (loop and inter connected) systems. The losses in the distribution system can be minimized by changing the existing radial distribution system into loop or interconnected systems by using tie lines or tie switches but it is always not possible because there are some limitations regarding with the tie line length. The reactive power increase in the system leads to poor voltage profile and increased power losses. To compensate the reactive power growth in the distribution system shunt capacitor banks are installed in the system, which will provide or generate required amount of vars at the point of installation. The capacitor banks are switched automatically in to the system by monitoring the load changes in the distribution system. The capacitor will reduce the line current which is drawn by the load in the system which results in voltage profile improvement, line loss reduction, better reliability and stability of the distribution system.

Neagle and Samson [1] considered the loss reduction from capacitors installed on primary feeders. In this method the peak power requirement was minimized. Cook [2] developed a formula for calculating loss reduction as afforded by shunt capacitor application, minimizing energy loss taking into account time

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variation of the load. Schmill [3] studied that the optimum location, sizing and timing of capacitor banks on feeders with uniformly distributed loads and randomly varying spot loads to evaluate reduction in costs of active and reactive losses without taking into account voltage regulation problem. He suggested a procedure of moments of the loads with respect to feeder resistance or reactance to calculate optimum ratings and locations of N-capacitor banks installed on a distribution feeder. Carlisle et Al. [4] Transfer of electric energy from the source of generation to the customer via the transmission and distribution networks is accompanied by losses. The majority of these losses occur on the distribution system. It is widely recognized that placement of shunt capacitors on the distribution system can lead to a reduction in power losses. Bae [5] developed an analytical method for the calculation of the power loss reduction by applying a number of shunt capacitors of same size, to a uniformly loaded feeder for a constant reactive load level. Mori, H et al. [6] proposed an efficient method for capacitor placement in distribution systems. The proposed method was based on parallel Tabu search that considered the decomposition of the neighborhood into sub neighborhoods and the multiple Tabu lengths in Tabu search.

In this paper the amount of capacitance required for achieving the required voltage tolerance limit and the percentage of power loss reduction at different capacitor values are determined.

## II. Problem Formulation

In general, the distribution operation and network upgradation can be done by feeder reconfiguration. It can be used to minimize line losses. The operational constraints have to be identified and satisfied. The aim consists of finding the radial configuration which reduces the system active power losses. Consider the line model and notation shown in Fig. 1.

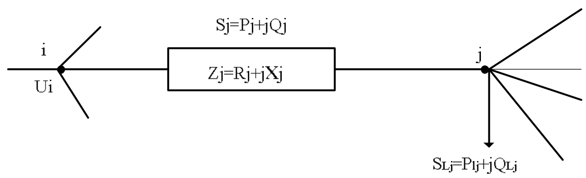


Figure 1. Loss model and notation

The real power loss equation between the two busses i and j is given as

$$P_{loss} = R_j \left[\frac{|V_i - V_j|}{Y_j}\right]^2 \tag{1}$$

Where,

i, j are two adjacent buses, $R_j$ : Resistance offered by the line section i,j, $V_i$ : Bus 'i' voltage, $V_j$ : Bus 'j' voltage

The loss minimizing function can be formulated as

$$P_{total} = min \sum P_{loss} = \sum R_j \left[\frac{|V_i - V_j|}{Y_j}\right]^2 \tag{2}$$

To solve the line loss optimization problem, we will use a set of power flow equations that are structurally rich and conductive to computationally efficient solution schemes. To illustrate them, consider the radial network in Fig.2.

We represent the lines with impedances $Z_l = r_L + jx_L$, and loads as constant power sinks, $S_L = P_L + Q_L$.

Power flow in a radial distribution network can be described by a set of recursive equations, called DistFlow branch equations, [7] that use the real power, and voltage magnitude at the sending end of a branch – $P_i$, $Q_i$, $V_i$ respectively to express the same quantities at the receiving end of the branch as follows[8].

$$P_{i+1} = P_i - r_i \frac{P_i^2 + Q_i^2}{V_i^2} - P_{Li+1} \tag{3.a}$$

$$Q_{i+1} = Q_i - x_i \frac{P_i^2 + Q_i^2}{V_i^2} - Q_{Li+1} \tag{3.b}$$

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) + (r_i^2 + x_i^2) \frac{P_i^2 + Q_i^2}{V_i^2} \tag{3.c}$$

Hence, if $P_o$, $Q_o$, $V_o$ at the first node of the network is known or estimated, then the same quantities at the other nodes can be calculated by applying the above branch equations successively. We shall refer to this Procedure as a forward update.

DistFlow branch equations can be written backward too, i.e. by using the real power, reactive power and the voltage magnitude at the receiving end of a branch. $P_i$, $Q_i$, $V_i$ to express the same quantities at the sending end of the branch. The result is the following recursive equations, called the backward branch equations.

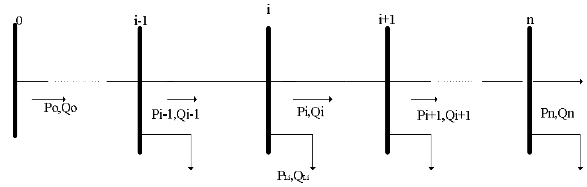


Figure 2. One line diagram of a radial network

$$P_{i-1} = P_i + r_i \frac{P_i^2+Q_i^2}{V_i^2} + P_{Li} \quad (4.a)$$

$$Q_{i-1} = Q_i + x_i \frac{P_i^2+Q_i^2}{V_i^2} + Q_{Li} \quad (4.b)$$

$$V_{i-1}^2 = V_i^2 + 2(r_i P_i + x_i Q_i) + (r_i^2 + x_i^2)\frac{P_i^2+Q_i^2}{V_i^2} \quad (4.c)$$

Where $P'_i=P_i+P_{Li}$ , $Q'_i=Q_i+Q_{Li}$.

Similar to forward update, a backward update can be defined: start updating from the last node of the network assuming the variables $P_n$, $Q_n$, $V_n$ at that point are given and proceed backwards calculating the same quantities at the other nodes by applying Eq (4) successively. Updating process ends at the first node (node 0) and will provide the new estimate of the power injections into the network, $P_O$, $Q_o$.

The power balance in the electrical system is the power drawn out of the system equals to the sum of the system load demand and power losses. According to power balance the power input to the feeders was in direct proportions to the power loss at the same load condition.

Figure 3 shows the basic schematic diagram for a simple two feeder radial system they are named as F#1 and F#2 the feeder F#1 consists of **j** number of buses and F#2 consists of **m** number of buses.$S_L$ is the apparent power at each load bus, **I** is the sectional current flowing through the feeder, $\mathbf{I_c}$ is the capacitor current and $\mathbf{\Delta I_m}$ is the Tie line current.

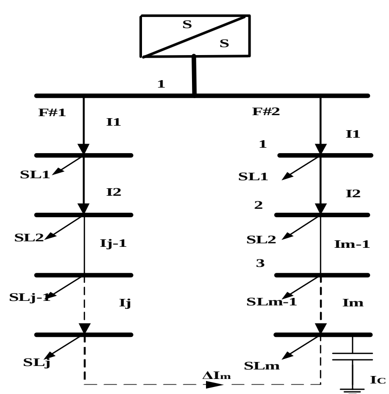


Figure 3. The Primary feeders with discrete load distribution

In the radial feeder system the real power loss of the feeder F#1 can be expressed as

$$P_{F\#1LOSS} = \left[\sum_{i=j}^{1}\left[\sum_{k=j}^{1} I_{LK}\right]^2 . R_i\right] \quad (5)$$

$$\left|I_{Lj}\right|^2 = \frac{P_{Lj}^2+Q_{Lj}^2}{V_j^2} \quad (6)$$

Where $P_{Lj}$, $Q_{Lj}$, and $V_j$, represent equivalent single phase active, reactive power demands and phase voltage, respectively. Besides $R_j$ is the line resistance in ohms per Kilometer.

The resistive line loss of the feeders F#2 can also be determined as

$$P_{F\#2LOSS} = [\sum_{i=m}^{1}[\sum_{k=m}^{1} I_{LK}]^2 . R_i] \quad (7)$$

The total loss of the feeders F#1and F#2 is given by

$$P_{LOSS}=PF_{\#1,\ LOSS}+PF_{\#2,\ LOSS} \quad (8)$$

When the reactive power is injected in to the system the sectional currents flowing in the system are changed this result in loss reduction and voltage profile improvement. The amount of change in sectional current is given by the equation 9.

$$I_{mnew}^2 = (I_m^2 cos\phi)^2 + (I_m^2 sin\phi - Ic)^2 \quad (9)$$

Here $I_{jnew}$ is the new sectional current after capacitor placement, $I_m$ is the sectional current at **m** th bus in feeder F#2 without capacitor and $I_c$ is the capacitor current.

$$P'_{F\#2LOSS} = [\sum_{i=m}^{1} [\sum_{k=m}^{1} I_{mnew}]^2 . R_i] \quad (10)$$

The total loss of the feeders F#1and F#2 after capacitor placing is given by

$$P'_{LOSS} = PF_{\#1,\ LOSS} + P'_{F\#2,\ LOSS} \quad (11)$$

Here $P'_{LOSS=}$total power loss of the feeders F#1 and F#2.$P'_{F\#1,LOSS=}$power loss in feeder F#1 after capacitor placement.$P'_{F\#2,LOSS=}$ power loss in feeder F#2 after capacitor placement.

Change in loss = $P'_{loss} - P_{LOSS}$

In this paper, the percentage of loss reduction is defined in two ways; one is in criterion of input power that is

$$LR_{P_{in}} = \left(\left(\frac{P'_{LOSS}}{P'_{in}}\right) - \left(\frac{P_{LOSS}}{P_{in}}\right)\right) \times 100\% \quad (12)$$

The other is in criterion of power loss, that is

$$LR_{PLoss} = \left({}^{\Delta P_{LOSS}}/_{P_{LOSS}}\right) \times 100\% \quad (13)$$

The loss reduction can be evaluated by (12) and (13).

Also the amount of maximum capacitance required for the percentage of voltage rise is given by eq.14.

$$QMAX = \frac{(\%VR \times 10 \times VL\text{^}2)}{(x \times l)} \quad (14)$$

Here QMax = the maximum capacitance required, %VR= percentage of voltage rise, VL=line-line voltage, x=reactance offered by the line, l=Length of the feeder from the sending end of the feeder to the capacitor location.

## III. NUMERICAL EXAMPLE

### *A. Test System Data & Simulation Cases*

Fig 4 shows the single line diagram of a sample two feeder distribution network with a substation of 132/33 KV. It consists of 30 MVA Transformer which is serving load through two feeders named as feeder F#1 and feeder F#2, which are supplying load to the urban area and the other is to a suburban area respectively. The Tie line with a length of 1200m is connected between the rear ends of the feeders F#1 and F#2 for making a radial system into ring main. The load density on both the feeders is almost equal i.e. 0.8290 on feeder F#1 and 0.8970 on feeder F#2. The normal operating phase current of the line is limited to 350 Amps because of the thermal limitations of the conductor and the line impedance of the line is Z=0.160+0.2620j ohms/Km. The voltage tolerance limitation of the feeder is considered about +6% to -9%. The static capacitor bank with a Capacitance of 8 MVAR is considered for the simulation purpose to simulate the different cases and conditions which are given below.

The shunt capacitor placed in the radial system can be operated mainly for two purposes they are

i) Voltage profile improvement.

ii) Active power loss reduction.

The simulation cases were illustrated as follows

CASE #A: Feeder F#2 is operating at a load of 1.2 p.u.

CASE #B: Feeder F#2 is operating at a load of 1.0 p.u.

CASE #C: Feeder F#2 is operating at a load of 0.8 p.u.

For the detailed analysis of numerical system, the above mentioned cases are simulated at three different conditions which are given below:

Condition#1: The Power factor (PF) at the substation is 0.707 PF.

Condition#2: The Power factor at the substation is 0.85 PF.

Condition#3: The Power factor at the substation is 0.95 PF.

The simulation of the test system shown in Fig: 4 is carried out by the data of the Network elements, as well as the loads, is presented in Table I.

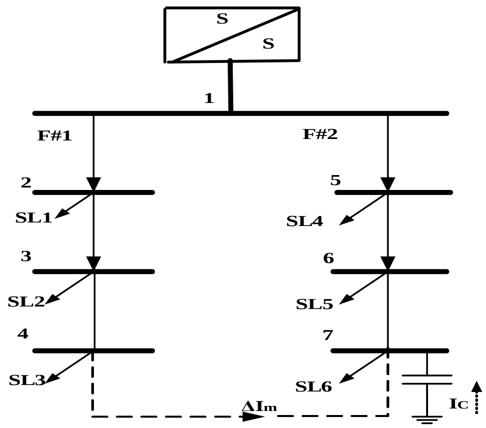


Figure 4. A Simple Two Feeder Radial Distribution Network

TABLE I. ILLUSTRATION OF SIMULATION CASE

| Feeder | Bus no | | Load (KVA) | Length (meters) |
|---|---|---|---|---|
| | From | To | | |
| F#1 | 1 | 2 | 3200 | 3420 |
| | 2 | 3 | 3660 | 4100 |
| | 3 | 4 | 3850 | 4510 |
| F#2 | 7 | 6 | 6085 | 6800 |
| | 6 | 5 | 5865 | 6400 |
| | 5 | 1 | 5453 | 6200 |
| Tie line | 4 | 7 | _ | 1200 |

*B) Simulation Results and Discussion*

The simulation results of the shunt capacitor placed in the system (which we considered) serves two purposes as mentioned above and they are discussed as:

*a) To achieve standard Voltage tolerance limits*

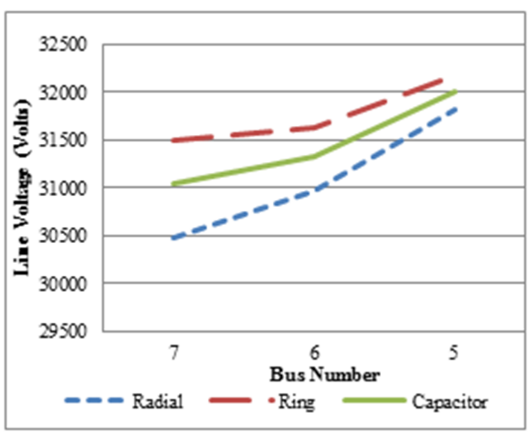


Figure 5. Voltage profile of Feeder F#2 for 1.2 P.u. load at 0.707 PF

The simulation results of case #A at condition 1 and condition 2 will give poor voltage profile (less than 0.94 p.u.) on feeder#2. For this a specified amount of capacitance is placed at bus 6 which is calculated by using Eq 14 for a particular amount of voltage rise to achieve good voltage profile by considering voltage violation limits. For this test system, the radial voltage magnitudes on feeder#2 at bus 5, 6, 7 are 31.83 Kv,

30.96 Kv, 30.48 Kv and 31.92 Kv, 31.13 Kv, 30.69 Kv at 0.707 PF and 0.85 PF respectively. Simulation results shows that a shunt capacitance of 5400 Kvar and 3500 Kvar is required at bus 7 to get reasonable voltage profile on feeder#2 for condition#1 and condition #2 respectively.

Figures 5, 6 represent the simulation results for the voltage profile improvement of feeder F#2 when the system is operating in radial, ring (with Tie line) and with a specified amount of shunt capacitance with an operating load of 1.2 p.u at 0.707 PF and 0.85 PF respectively.

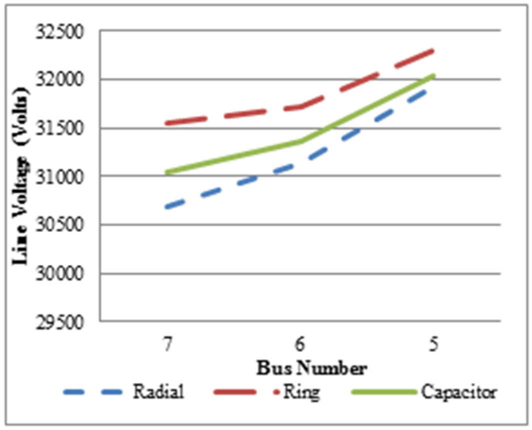


Figure 6. Voltage profile of Feeder F#2 for 1.2 P.u. load at 0.85 PF

*B. Active power loss reduction*

The shunt capacitor placed in the system also serves for the purpose of loss reduction. The tabular forms table II, III and IV shown below represents the simulation results of the test system which represents, the power loss in kw with and without capacitor placement, power input, percentage loss reduction in terms of input power and percentage of loss reduction when the feeder F#2 is operating at three different load conditions 1.2 p.u, 1.0 p.u and 0.8 p.u by considering different conditions which are mentioned in earlier sections.

Figures 7, 8, 9 shown below represents the percentage of loss reduction while comparing with radial system when the feeder F#2 is operating at a load of 1.2 p.u, 1.0 p.u and 0.8 p.u respectively at different operating power factor values of 0.707 pf, 0.85 pf and 0.95 pf and for different p.u shunt capacitance rating, which is placed at BUS 7.

TABLE II. THE SIMULATION RESULTS OF CASE#A

| | **P.u.Capacitance** | **0** | **0.2** | **0.4** | **0.6** | **0.8** | **1** |
|---|---|---|---|---|---|---|---|
| **0.707 PF** | **P Loss (kw)** | 850.30 | 749.93 | 681.17 | 647.82 | 651.69 | 689.89 |
| | **P in (kw)** | 23187 | 23087 | 23018 | 22984 | 22988 | 23027 |
| | **LR Pin %** | 0 | -0.4188 | -0.7078 | -0.8486 | -0.8322 | -0.6711 |
| | **LR Ploss %** | 0 | 11.803 | 19.889 | 23.812 | 23.35 | 18.865 |
| **0.85 PF** | **P Loss1 (kw)** | 841.47 | 770.32 | 732.15 | 728.01 | 756.16 | 812.47 |
| | **P in1 (kw)** | 27696 | 27625 | 27587 | 27583 | 27611 | 27667 |
| | **LR Pin %** | 0 | -0.2498 | -0.3842 | -0.3989 | -0.2996 | -0.1017 |
| | **LR Ploss %** | 0 | 8.456 | 12.992 | 13.484 | 10.139 | 3.447 |
| **0.95 PF** | **P Loss2 (kw)** | 827.28 | 789.32 | 783.51 | 808.31 | 860.38 | 935.76 |
| | **P in2 (kw)** | 30841 | 30803 | 30797 | 30822 | 30874 | 30950 |
| | **LR Pin %** | 0 | -0.1199 | -0.1383 | -0.0599 | 0.1043 | 0.3411 |
| | **LR Ploss %** | 0 | 4.588 | 5.290 | 2.292 | -4.002 | -13.114 |

TABLE III. THE SIMULATION RESULTS OF CASE#B

| P.u.Capacitance | | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|---|---|---|---|---|---|---|---|
| 0.707 PF | **P Loss (kw)** | 611.43 | 533.51 | 486.82 | 475.70 | 499.91 | 553.47 |
| | **P in (kw)** | 20487 | 20409 | 20363 | 20352 | 20376 | 20429 |
| | **LR Pin %** | 0 | -0.3704 | -0.5937 | -0.6470 | -0.5310 | -0.2752 |
| | **LR Ploss %** | 0 | 12.743 | 20.380 | 22.199 | 18.240 | 9.480 |
| 0.85 PF | **P Loss1 (kw)** | 606.40 | 552.27 | 530.52 | 541.73 | 582.60 | 647.90 |
| | **P in1 (kw)** | 24502 | 24448 | 24427 | 24438 | 24479 | 24544 |
| | **LR Pin %** | 0 | -0.2159 | -0.3030 | -0.2581 | -0.0948 | 0.1649 |
| | **LR Ploss %** | 0 | 8.925 | 12.513 | 10.665 | 3.924 | -6.845 |
| 0.95 PF | **P Loss2 (kw)** | 598.25 | 571.07 | 575.21 | 608.43 | 666.54 | 745.33 |
| | **P in2 (kw)** | 27306 | 27278 | 27283 | 27316 | 27374 | 27453 |
| | **LR Pin %** | 0 | -0.0974 | -0.0826 | 0.0365 | 0.2440 | 0.5241 |
| | **LR Ploss %** | 0 | 4.542 | 3.850 | -1.703 | -11.417 | -24.587 |

TABLE IV. THE SIMULATION RESULTS OF CASE#C

| P.u.Capacitance | | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|---|---|---|---|---|---|---|---|
| 0.707 PF | **P Loss (kw)** | 422.59 | 365.54 | 339.88 | 349.49 | 389.90 | 453.17 |
| | **P in (kw)** | 17838 | 17781 | 17755 | 17765 | 17805 | 17868 |
| | **LR Pin %** | 0 | -0.3133 | -0.4548 | -0.4017 | -0.1792 | 0.1671 |
| | **LR Ploss %** | 0 | 13.501 | 19.574 | 17.298 | 7.735 | -7.237 |
| 0.85 PF | **P Loss1 (kw)** | 419.95 | 381.61 | 375.15 | 399.85 | 450.28 | 520.87 |
| | **P in1 (kw)** | 21357 | 21319 | 21313 | 21337 | 21388 | 21458 |
| | **LR Pin %** | 0 | -0.1763 | -0.2061 | -0.0923 | 0.1390 | 0.4611 |
| | **LR Ploss %** | 0 | 9.131 | 10.668 | 4.786 | -7.222 | -24.031 |
| 0.95 PF | **P Loss2 (kw)** | 415.65 | 398.33 | 411.40 | 451.38 | 513.23 | 592.94 |
| | **P in2 (kw)** | 23816 | 23799 | 23812 | 23852 | 23914 | 23994 |
| | **LR Pin %** | 0 | -0.0715 | -0.0176 | 0.1472 | 0.4009 | 0.7260 |
| | **LR Ploss %** | 0 | 4.166 | 1.024 | -8.595 | -23.476 | -42.654 |

## IV. CONCLUSION

The effect of shunt capacitor placed at a particular location in a simple two feeder radial distribution system is evaluated in this paper by considering different cases and conditions using MATLAB simulation. The results of the shunt capacitor placement are compared with the simple radial and loop type networks. From figures 5, 6 it is noted that the voltage profile can be improved by changing the radial system into ring main system, and also by using shunt capacitor. From figures 7, 8, 9 it is noted that the percentage of loss deduction is maximum only for a particular amount of capacitance otherwise it leads to more power losses than a normal system. Sometimes it leads to the over voltages i.e., beyond the voltage tolerance limits because of more capacitance which supplies more reactive power into the system.

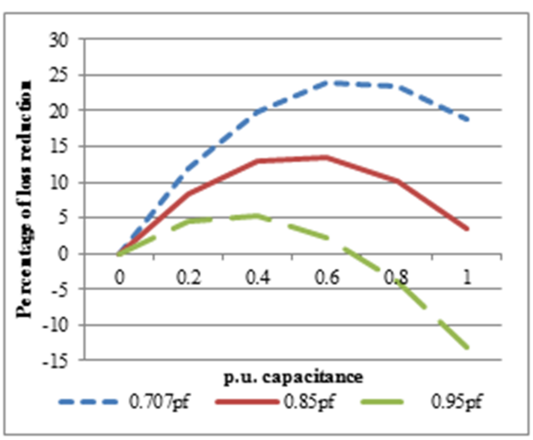


Figure 7. Percentage of loss reduction for 1.2 p.u Load on F#2

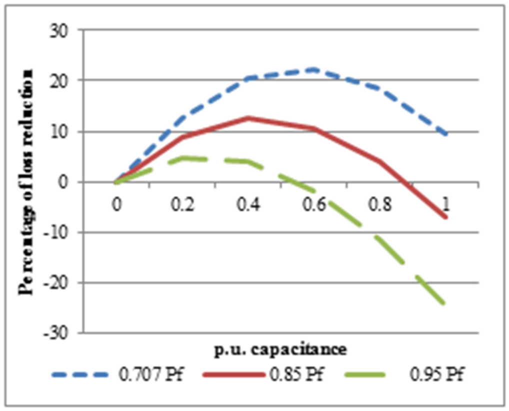


Figure 8. Percentage of loss reduction for 1.0 p.u Load on F#2

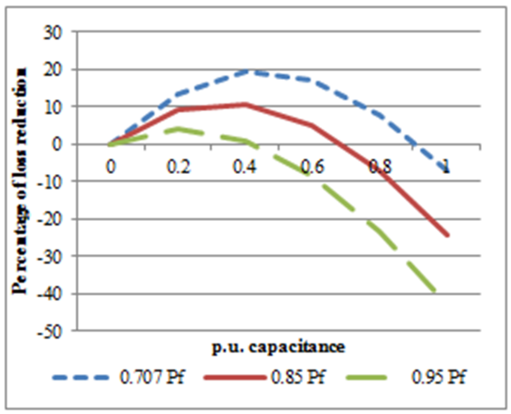


Figure 9. Percentage of loss reduction for 0.8 p.u Load on F#2

By closure of this paper we conclude that the voltage profile improvement and loss reduction in ring main system is better than placing a shunt capacitor at load point. But it is always not possible to reconfigure the system from radial to ring main. It is only possible for certain distance. In that case it is better to go for shunt capacitor placement. By proper implementation of shunt capacitor in the distribution system we can achieve both voltage profile improvement and line loss reduction; thereby the system capacity can also be increased.

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